AN APPROACH TO MODELING LANDUSE CHANGE AND FOREST MANAGEMENT ON A GLOBAL SCALE

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Abstract: A geographically explicit approach to modelling landuse change and forestry on a global scale and a respective model are presented. The model simulates decisions of virtual land owners on landuse change (afforest or deforest) and forest management. The decisions are made in cells of a regular geographic grid (e.g. 0.5x0.5 deg). Landuse change decisions are based on comparison of net present values of forestry and agriculture. Forest management decisions are taken considering wood demand, forest productivity and net present value of forestry comparing to a baseline. Pricing of carbon stored in forest biomass, litter and soil alters forest net present value thus influencing landuse change and forest management decisions. Proposed approach allows estimation of marginal abatement costs for Reduced Emissions from Deforestation and Forest Degradation (REDD) comparable across countries or regions.

1 INTRODUCTION

Researchers often face a problem: how to make a detailed projection comparable across many countries? Similar approach should be applied to all countries. In case of modelling landuse change and forest management amount of consistent data available in countries differs and in most cases is limited to the data compiled by the international organisations (e.g., Food and Agriculture Organisation – FAO, secretariat of the United Nations Framework Convention on Climate Change – UNFCCC, the Ministerial Conference on the Protection of Forests in Europe – MCPFE etc.) or global studies like Global Land Cover 2000 (JRC, 2003), multimodel net primary production (NPP) assessment (Cramer et al., 1999) etc. Also a limited number of projections of factors that can be used as drivers of landuse change and forest management on country scale or a finer scale (e.g., GGI Scenario Database, 2007) exist.

The problem is to find among the data a set of drivers that can describe the landuse change and forest management patterns plausibly.

Benítez and Obersteiner (2003) applied comparison of net present values (NPV) of alternative land uses as a core of landuse change decision making on a grid-cell scale of a geographically explicit model for Latin America. In such approach the main landuse change drivers are gross domestic product (GDP), population density, forest productivity, forest share and agriculture suitability of the land. The approach was found successful and was further developed by Kindermann et al. (2006), Benítez and Obersteiner (2007) and Gusti et al. (2008). The model was named Global Forest Model (G4M). Modeling of forest management was introduced into the model to take into account interdependence of afforestation, deforestation and forest management processes (Gusti, 2010 a, b).

Current version of G4M is designed to provide projections of afforestation and deforestation rates, forest management options and respective carbon dioxide emissions and sinks, and their response to

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climate policies in a form of carbon tax or incentive payments. The model can help in policy assessment for the ongoing international negotiations on agriculture, forestry and other land use and REDD in the frameworks of the post-Kyoto climate agreement. G4M results have been used for a number of assessments such as the Eliash Review, the Economic Assessment of Post-2012 Global Climate Policies, Roadmap for Moving to a Low-carbon Economy in 2050, and applications www.forestcarbonindex.org and OSIRIS. The latest model results are discussed in (Böttcher et al, 2011).

Objective of the paper is to present the latest developments of the modeling approach and the model description in an integrated manner. A number of new features were developed since the last publications containing comprehensive model description (Kindermann et al., 2006) and (Gusti et al., 2008). The new features are: virtual forest, forest management, interaction of landuse change between grid cells, interaction of landuse change and forest management. The model structure has been modified as well.

2 MODEL DESCRIPTION

2.1 General Structure of the Model

Thematically the Global Forest Model is composed of three parts – environmental (natural conditions and forest parameters), economic (estimation of local - cell specific - wood and agricultural land prices, NPV of forestry and agriculture, forest harvesting and planting costs) and decisions (decisions on forest management parameters and landuse change). The model flowchart is shown in figure 1.

The model consists of five major modules: Virtual forest, Forest initialisation, Forest management decisions, Landuse change decisions and Forest dynamics. The virtual forest module simulates forest growth and management on a forest scale. It is used in the other modules. The forest initialisation is run only once at the very beginning. The module creates forest in each cell and sets initial parameters of the forests according to observed values. The forest management decisions module is run every year to adjust forest rotation length and thinning to match wood demand on country or region scale taking into account carbon sequestration policies. The landuse change decisions module is run every year to estimate NPV of forestry and agriculture in order to set the cell to one of the three states – afforest/deforest/no change, and estimate rate of the landuse change. The forest dynamics module applies forest management and landuse change with the estimated parameters to the virtual forest.

To take into account influence of trade by wood and agriculture commodities on the local prices of wood and agricultural land G4M is linked with the global biomass optimisation model (GLOBIOM, www.globiom.org).

2.2 Virtual Forest Module

The module simulates forestry on a scale of huge forests. A generic forest growth function is in the module core. The module allows creation of a forest with specified environmental and forest management parameters including growth function parameters, highest mean annual increment of a normal forest - MAI, yield table stocking degree - SD, rotation length - RL, thinning, harvest losses, forest area and age structure information. Forest is represented with a set of forest plots of N age classes (N=RL+1; one year step) of different area determined by the forest age structure. Forest parameters (biomass, height and diameter of trees) develop with age following the growth function and scaled by MAI.

The virtual forest module provides thinning and harvest according to the specified parameters bringing forest to "normal" state gradually. The module determines RL that is optimal for getting maximal mean annual increment and maximal sustainable harvest every year (RL_{MAI}), getting maximal biomass (RL_{maxBm}), or keep current biomass (RL_{Bm}) for specific growth conditions described by the highest mean annual increment (MAI) and thinning intensity described by the stocking degree related to yield tables (SD). Usually RL_{MAI} is the shortest, and RL_{maxBm} is the longest among the rotation lengths considered.

2.3 Forest Initialisation Module

In each grid cell, where forest exists according to an initial land cover map (e.g. GLC 2000 can be used (JRC, 2003)) or can grow, if planted according to potential vegetation map (Rammakuty and Foley, 2009) two virtual forests are created – 'old forest' and 'new forest'. Area of the old forest is set to the observed one and area of the new forest is set to 0. Mean annual increment is estimated from the NPP map (Cramer et al., 1999).

Site parameters averaged over a grid cell (climate, soil type, altitude, slope and NPP) determine forest productivity and, together with country scale economic data, land price and harvesting costs.

The forest parameters are initialized iteratively using geographically explicit or country specific information. Increment is determined using a map of potential NPP translated into MAI. MAI was scaled at country level to match MCPFE data. Age structure and SD are used as additional information for adjusting MAI. If SD of forest modelled with a given age structure (country average) in a cell is > 1.05, age structure of the modelled forest is shifted iteratively by a few years towards older forest. If stocking degree of forest modelled in a cell is < 0.5, age structure of the modelled forest is shifted iteratively by a few years towards younger forest.

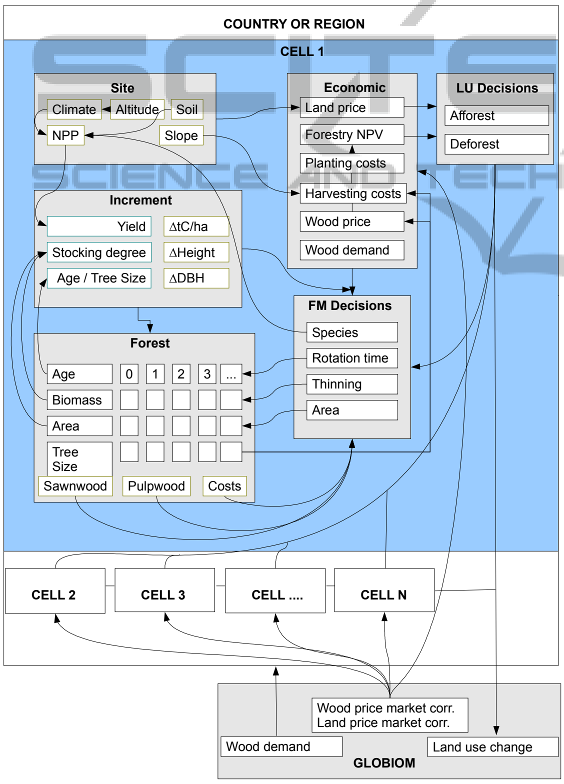

Figure 1: Global Forest Model flowchart.

It is required that the shifts are symmetrical to keep country average age structure close to statistical value. If the age structure shift distribution is skewed towards older forest, the country's average MAI is increased iteratively. If the age structure shift distribution is skewed towards younger forest, country's MAI is decreased iteratively.

In case of non-uniform age structure SD is determined as a relation of yield table biomass of a fully stocked stand to the observed biomass. If age structure information is not available, normal forest is created and SD is set to one.

Six forest management types that influence further forest management decisions are identified depending on site productivity, initial forest management map (FM_{map}) and profitability of forestry comparing to agriculture (Gusti 2010a).

Rotation length of managed forests is set to RL_{MAI}, RL_{Bm} or RL_{maxBm} depending on whether wood harvest within a country is smaller, equal or greater than domestic wood demand. If RL_{Bm} is smaller than RL_{MAI} we use RL_{MAI} to avoid transition effect resulting in temporal decrease of harvest even if the rotation length is changed to RL_{MAI}.

2.4 Forest Management Decisions Module

Every simulation year all cells are processed one by one. In the input file, which contains data for each grid cell, the cells are sorted by countries, then descending by MAI, amount of carbon in aboveground biomass, forest area, population density and agriculture suitability. Thus productive forests of larger area and closer to populated places are processed first. Harvested wood in a cell is a sum of final harvest, pre-final harvest (thinning) and wood obtained from deforestation decreased by a country-specific slash burn factor. A sum of harvested wood in a country is compared to domestic demand in the country. If demand is greater than supply by more than 2%, rotation length of forest in cells (that belong to the country) is decreased gradually (five-year time step) up to RL_{MAI} one by one until demand is satisfied. If after processing all cells in the country, demand is still greater than supply by 2%, unmanaged forest is turned to managed, cells with population >0 or with more productive and profitable forest are taken first.

If harvest in a country is greater than demand by 2% rotation length of less productive forests is increased gradually (five-year time step) up to RL_{maxBm}. If after processing all cells in the country, harvest is still greater than demand by 3%, RL of managed forests in the country is increased gradually up to RL_{maxBm} until the 3% threshold is reached. Forest management type is changed to unmanaged if the supply-demand difference is more than 5% after the previous actions.

When modeling forest management response to a carbon sequestration incentive in a form of carbon tax with a carbon price we consider a hierarchy of interests: country must provide wood amount matching the demand and create conditions for carbon sequestration (both are on country scale) by adjusting forest management; every year forest owners adjust forest management to get NPV not smaller than the NPV at zero carbon price (NPV_{bau}). Wood production satisfying wood demand at country scale is of the highest priority. We use a two step procedure.

STEP1. Every year, starting from 2011, forest management in each cell is disturbed by increasing RL. For the forest used for wood production, where NPV estimated for the RL_{maxBm} (NPV_{wc}) is greater than the NPV_{bau} ($NPV_{bau} \geq 0$), RL is increased proportionally to the (NPV_{wc}-NPV_{bau})/NPV_{bau}. If the NPV condition is not satisfied RL is increased proportionally to the carbon price and saturates at 50$/tC reaching 5 year increment. In all cases $RL \leq RL_{maxBm}$. NPV for the new RL is estimated (NPV_c). NPV in all cases is estimated for the time span left to the end of the period considered.

STEP 2. Since production of wood balancing wood demand has higher priority than the carbon sequestration, after Step 1 the forest management of forests within each country is adjusted to harvest as much wood as the country wood demand. When adjusting the forest management it is required the new NPV multiplied by an adjustment hurdle coefficient to be greater or equal NPV_c estimated on Step 1. The adjustment hurdle varies from 1 to 2500. If the total harvest does not match wood demand, the hurdle is increased by 0.3 and the forest management adjustment is repeated for the forests within the country again. Total number of iterations is limited to 50 to avoid infinite loops. We assume that the forest owners getting NPV smaller than NPV_{bau} are compensated by the government that is not reflected in the algorithm explicitly.

2.5 Landuse Change Decisions Module

Land use change decisions for each grid cell are made by comparing NPV of forestry and NPV of agriculture. Deforestation happens in a cell if the NPV of agriculture plus benefits from selling wood after clear-cut is greater than the NPV of forestry multiplied by a hurdle coefficient (a calibration parameter that captures institutional barriers to sustainable forest management). Afforestation happens in a cell, in which the environmental conditions are suitable for forestry and the NPV of forestry is greater than the NPV of agriculture.

The NPV of forestry is a function of the MAI, stumpage wood price and planting costs. The MAI together with rotation length determine amount of harvestable wood. Stumpage wood price is a function of non-forest area and population density in the grid cell. Planting costs are defined through planting costs in the reference country (Brazil) decreased by natural regeneration in the grid. Stumpage wood price and planting costs are scaled by purchasing power parity (PPP) relative to the reference country.

The NPV of agriculture is modelled with an agricultural land price in a form of Cobb–Douglas production function, in which agricultural suitability and population density are independent variables. The NPV of agriculture in current grid is scaled by PPP relative to the reference country. To take into account deforestation pressure on forest frontier in neighbour cells the NPV in current cell is modified proportionally to the largest non-forest land area in surrounding cells.

The deforestation rate (amount of forest land that can be converted to agricultural land during one year), and afforestation rate represent differences in capacity to implement land use changes, e.g. technical, infrastructural and financial capabilities of deforesting or establishing new forests. Thus, deforestation and afforestation rates are modelled as a function of GDP, population density, forest area and agricultural suitability.

2.6 Forest Dynamics Module

The forest dynamics module applies estimated forest management parameters to the virtual forest, inserts harvested wood and forest biomass into respective arrays to form output data. Then the forest management decisions are executed and consistency check is done.

In the module emissions caused by deforestation and carbon sink due to afforestation are estimated. The emissions from deforestation include emissions from burning of slash, dead wood and coarse roots, and from decomposition of wood products, litter and soil organic matter. The afforestation carbon sink is due to biomass increment in growing trees, accumulation of forest litter and soil organic matter. To assess the emissions and carbon sink dynamics we track evolution of all carbon pools over time applying ecosystem-specific emission rates.

If impact of climate policy is estimated all of the carbon pools are credited or debited. The emitted (or sequestered) carbon multiplied by the carbon price enters the NPV comparison for landuse change decision making.

2.7 Input Data

G4M uses parameters that are defined on different scales: global (e.g., decay rate of long and short living products, carbon price), regional (e.g., relative stumpage wood price and net present values of agriculture), country (e.g., corruption factor, risk-adjusted discount rate, forest planting costs, GDP, hurdle, afforestation and deforestation rate adjustment coefficients) and grid (e.g., population density, agricultural suitability, NPP, forest biomass, litter and coarse woody debris, potential vegetation, protected areas, etc.). Some model parameters change with time following B2 IPCC scenario: population density, GDP (market), minimum agricultural land secured to feed the population and land under infrastructure. Main parameters of the model and data sources are summarized in Table 1.

Table 1: Main G4M parameters.

Parameter	Resolution	Reference
Relative price change for wood and agriculture land	Region	GLOBIOM
PPP	Country	World Bank, 2005
MAI	Country	MCPFE http://forestportal.efi.int/view.php?id=1895&c=E1
Slash burn factor	Country	Kindermann et al., 2006
GDP, Population density	0.5x0.5 deg	Grubler et al. 2007
Land under infrastructure, secured cropland	0.5x0.5 deg	Tubiello and Fischer, 2007
Forest share	0.5x0.5 deg	JRC, 2003
NPP	0.5x0.5 deg	Cramer et al. 1999;
Potential vegetation	0.5x0.5 deg	Ramankutty and Foley, 1999
Agriculture suitability	0.5x0.5 deg	Ramankutty et al., 2002
Forest biomass, litter and coarse woody debris	0.5x0.5 deg	Kindermann et al., 2008b
Protected forest	0.5x0.5 deg	WDPA Consortium, 2004

2.8 Model Interlink with GLOBIOM

In G4M the prices of agricultural land and wood are local, i.e. they are estimated for each grid-cell independently. Thus commodity market effects are not taken into account. But in reality interregional trade influences the prices and consequently land-use change and forest management decisions. To take into account the commodity market effects we linked G4M with a bottom-up partial equilibrium model of total land use GLOBIOM (www.globiom.org), which is being developed at IIASA. G4M provides GLOBIOM with initial prices of stumpage wood and agricultural land, which are averaged for 27 world regions. Using the initial prices and the carbon price GLOBIOM calculates dynamics of the prices. In G4M the prices for each grid cell are estimated by multiplication of the grid cells' prices for the base year and respective price changes for the respective region of GLOBIOM.

GLOBIOM determines equilibrium commodity prices for agricultural and forest sectors, matching supply quantities with demand quantities for regional aggregates accounting for interregional trade. Population and GDP driving basic demand for forest products and agricultural commodities follow similar trajectory as in G4M.

2.9 Model Calibration and Validation

Afforestation and deforestation rates are controlled with three country-specific calibration coefficients: afforRate, deforRate and hurdleLUC. The hurdleLUC coefficient controls balance of the forestry NPV and agriculture NPV thus influencing the landuse change decisions. The afforRate and deforRate control afforestation and deforestation rates in the cells where one of the processes is active. Using the coefficients one can calibrate the model to match country landuse change data averaged over a certain period. Matching a trend in the landuse change rate is also possible if data for more than one period is available. In particular we used FAO (FAO, 2010) or UNFCCC (www.unfccc.int) data for the calibration depending on requirements of a project for which the model is run.

The model performance was tested against independent estimates for Ukraine (Gusti et al., 2009) as well as by comparison with similar models (Kindermann et al., 2008b). G4M sensitivity was studied by Gusti (2010c). Recently G4M has been validated with national experts of individual countries in the European Union.

4 CONCLUSIONS

Presented approach to modelling afforestation, deforestation and forest management in one complex model allows taking into account interactions between the processes and making assessment of REDD policies applying similar method in all countries. The model is designed to use data available at different scales (from local, grid cell specific to global). One of the important requirements to the data composition is consistency of all constituents. The approach proves its validity by providing plausible results compared against independent estimates and tested by national experts in EU countries. The model results are widely used for integrated assessment purposes or in other applications.

Further research: To improve performance of the model in tropics we plan to introduce initialisation of deforestation in cells using remote sensing data and add a road network that is shown to be an important deforestation driver (Kirby et al, 2006).

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REFERENCES

Benitez P. C. and Obersteiner M., 2006. Site identification for carbon sequestration in Latin America: A grid-based economic approach. *Forest Policy and Ecconomics*, 8:636–651.

Böttcher H., Verkerk H., Gusti M. et al. 2011. Projection of the EU27 forest carbon sink and effects of recent bioenergy policies using two advanced forestry models. *Under preparation*

Cramer W, Kicklighter D. W, Bondeau A. et al, 1999. Comparing global models of terrestrial net primary productivity (NPP): Overview and key results. *Global Change Biology,* 5(S1): 1–15.

FAO, 2010. Global Forest Resources Assessment 2010. Main Report. *Food and Agriculture Organization of the United Nations*, Rome, 2010, 375p.

GGI Scenario Database, 2007. *International Institute for Applied System Analysis (IIASA) GGI Scenario Database*, http://www.iiasa.ac.at/Research/GGI/DB/

Grubler A., Nakicenovic N., Riahi K. et al, 2007. Integrated assessment of uncertainties in greenhouse gas emissions and their mitigation: Introduction and overview. *Technological Forecasting and Social Change*, 74 (7): 873-886

Gusti M., Havlik P., Obersteiner M., 2008. Technical Description of the IIASA Model Cluster. *The Eliasch Review.* Office of Climate Change, UK.

Gusti M., Havlik P., Obersteiner M., 2009. How much additional carbon can be stored in forests if economic measures are used and how much could it cost? *Research Reports of the National University of Bioresources and Nature Management of Ukraine*, Issue 135.

Gusti M., 2010a. An Algorithm for Simulation of Forest Management Decisions in the Global Forest Model. *Artificial Intelligence*, 4: 45-49

Gusti M., 2010b. An Algorithm for Simulation of Forest Management Response to Carbon Price Incentive. *Proceedings of the conference 'Modern Information Technologies in Economy, Management and Education"*, 12 November 2010 Lviv, pp. 94-97

Gusti M., 2010c. Uncertainty of BAU emissions in LULUCF sector: Sensitivity analysis of the Global Forest Model. *Proceedings of the 3rd International Workshop on Uncertainty in Greenhouse Gas Inventories*, LPNU, Lviv, 299p. - pp.73-80.

JRC 2003. The Global Land Cover Map for the Year 2000. GLC2000 database. *European Commission Joint Research Centre*; http://www-gvm.jrc.it/glc2000

Kindermann G., Obersteiner M., Rametsteiner E. and McCallcum I., 2006. Predicting the Deforestation–Trend under Different Carbon–Prices. *Carbon Balance and Management*, 1:15

Kindermann G., McCallum I., Fritz S., Obersteiner M., 2008a. A global forest growing stock, biomass and carbon map based on FAO statistics. *Silva Fennica*, 42(3): 387-396

Kindermann G., Obersteiner M., Sohngen B., et al, 2008b. Global cost estimates of reducing carbon emissions through avoided deforestation. *PNAS*, 105 (30): 10302–10307.

Kirby K., W. Laurance, A. Albernaz, et al. 2006. The future of deforestation in the Brazilian Amazon. *Futures*, 38: 432-453

Ramankutty N., Foley J. A., Norman J., McSweeney K., 2002. The global distribution of cultivable lands: current patterns and sensitivity to possible climate change. *Global Ecology & Biogeography*, 11(5): 377-392.

Ramankutty, N., and J. A. Foley, 1999. Estimating historical changes in global land cover: croplands from 1700 to 1992. *Global Biogeochemical Cycles,* 13(4): 997-1027.

Tubiello F. N., Fischer G., 2007. Reducing climate change impacts on agriculture: Global and regional effects of mitigation, 2000-2080. *Technological Forecasting and Social Change*, 74 (7): 1030-1056

WDPA Consortium, 2004. World Database on Protected Areas. *Copyright World Conservation Union (IUCN) and UNEP-World Conservation Monitoring Centre*.

World Bank, 2005. World Development Indicators. *World Bank*.